Nuclear TMDs at CLAS12

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Outline

- nuclear medium and partonic transverse momenta
- TMDs in SIDIS
- ϕ-mudulation of the SIDIS cross section and asymmetries
- benchmark on a proton target with HERMES data
- GOAL : working model that can be supplemented with nuclear effect to study the modification of the asymmetries in SIDIS on nuclear targets

Transverse momentum in nuclear reactions

- Let us consider the semi inclusive process : $l + A \to l + \pi^+ X$
  - PDFs modification inside nucleus
  - modification of fragmentation
- $f_q^A(x, k_\perp) \approx \frac{A}{\pi \Delta_{2F}} \int d^2\ell_\perp e^{-(\vec{k}_\perp - \vec{\ell}_\perp)^2/\Delta_{2F}} f_q^N(x, \ell_\perp)$
- total average squared transverse momentum broadening $\Delta_{2F} = \int d\xi_N^- \hat{q}_F(\xi_N)$
- $\hat{q}_F(\xi_N)$ is the quark transport parameter.
- This contribution is directly linked with the final state interaction increase expected in a nucleus compare to a proton target.
- In a pure parton energy loss model, $\hat{q}_F(\xi_N)$ encodes the effect of the nuclear material on an outgoing quark, while the fragmentation functions are considered unchanged.

The transport parameter

- The transport parameter is widely used
  - in the heavy ion collision community and
  - in the hadronization community
- fundamental parameter governing the energy loss of partons crossing QCD matter.
- It is defined as the average transverse momentum square acquired by a parton per unit of length of nuclear material crossed.
- Interestingly, the quark transport parameter has been directly related to the gluon density in the nucleus:

$$\hat{q}_F(\xi_N) = \frac{2\pi^2\alpha_s}{N_c}\rho_N^A(\xi_N)[xf_g^N(x)]_{x=0}$$

where $\rho_N^A(\xi_N)$ is the spatial nucleon number density inside the nucleus and $f_g^N(x)$ is the gluon distribution function in a nucleon.

Strategy

- IF partonic transverse momenta are sensitive to the transport coefficient

  THEN the most sensitive terms in SIDIS cross section are the ϕ-dependent ones.

- THEREFORE $\hat{q}$ leads to a direct modification of SIDIS asymmetries generated at the parton level:
  Liang, Wang, and Zhou, PRD77 (2008) 125010,
  Gao, Liang and Wang PRC81, (2010) 065211

- we are building a representation of the SIDIS cross section on nucleon
  - which takes in account all angular modulations;
  - which implements the best knowledge accumulated so far in phenomenological analyses;

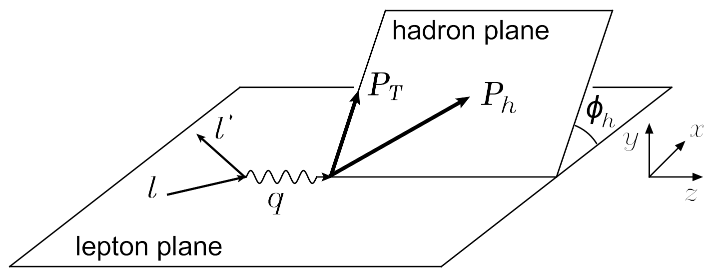
- observable benchmarks against HERMES data with target proton on:
  – multiplicities, pt-spectra, $\langle \cos\phi \rangle$, $\langle \cos 2\phi \rangle$, $\langle \sin\phi \rangle$

- GOAL is to implement nuclear effects on the same observables

SIDIS : reference frame and labels

- We consider the semi-inclusive DIS reaction

$$e(\ell) + N(P) \to e(\ell') + h(P_h) + X(P_X)\,,$$



- lab reference frame : virtual photon momentum defines the z axis
- DIS variables : x_B, y, and Q^2
- $z_h = E_h/\nu$, E_h energy of detected hadron in lab frame
- $\boldsymbol{P}_T$: the transverse momentum of the detected hadron h
- ϕ_h : azimuthal angle of the hadron vs lepton plane

SIDIS cross section decomposition

- The differential cross section of SIDIS for a longitudinally polarized beam with helicity λ_e scattered off an unpolarized hadron is generally expressed as

$$\frac{d\sigma}{dx_B\, dy\, dz\, d\phi\; dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{x_B y Q^2} \frac{y^2}{2\,(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x_B}\right) \Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\, \cos\phi\, F_{UU}^{\cos\phi}$$

$$+ \varepsilon\cos(2\phi)\, F_{UU}^{\cos 2\phi} + \lambda_e \sqrt{2\,\varepsilon(1-\varepsilon)}\, \sin\phi\, F_{LU}^{\sin\phi} \Big\}$$

- $\gamma = \frac{2Mx}{Q}$
- ratio of the longitudinal and transverse photon flux ε is defined as

$$\varepsilon = \frac{1-y-\gamma^2 y^2/4}{1-y+y^2/2+\gamma^2 y^2/4}$$

Convolutions in transverse space

- In the parton model, F_{UU} and F_{LU} can be expressed as the convolutions of twist-2 and twist-3 TMD DFs and FFs

$$\mathcal{C}[wfD] = x \sum_q e_q^2 \int d^2\boldsymbol{k}_T \int d^2\boldsymbol{p}_T \delta^2(z\boldsymbol{k}_T - \boldsymbol{P}_T + \boldsymbol{p}_T) \times w(\boldsymbol{k}_T, \boldsymbol{p}_T) f^q(x, \boldsymbol{k}_T^2) D^q(z, \boldsymbol{p}_T^2) \quad (1)$$

- $\boldsymbol{p}_T$: transverse momentum of the hadron with respect to the direction of the fragmenting quark
- $\boldsymbol{k}_T$: intrinsic transverse momentum of the quark inside the nucleon
- $\boldsymbol{P}_T = z\boldsymbol{k}_T + \boldsymbol{p}_T$

Structure functions: details

- Relevant structure functions can be expressed as

$$F_{UU} = \mathcal{C}[f_1 D_1], \tag{2}$$

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{p}_{\boldsymbol{T}}}{zM_h}\left(x_B\, eH_1^{\perp}\right) + \frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{k}_{\boldsymbol{T}}}{M}\left(x_B\, g^{\perp} D_1\right)\right], \tag{3}$$

- $e(x)$ and $g^{\perp}(x)$ twist-3 distribution
- $H_1^{\perp}(z)$ and $D_1(z)$ Collins and unpolarised FFs, respectively
- M_h is the mass of the final-state hadron
- $\hat{\boldsymbol{P}}_T = \frac{\boldsymbol{P}_T}{P_T}$ with $P_T = |\boldsymbol{P}_T|$.
- similar for the other ϕ-modulations

The Cahn effect

- Let assume a gaussian pt dependence
  - $f_q(x, k_\perp) = f_q(x) \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2/\langle k_\perp^2 \rangle}$
  - $D_q^h(z, p_\perp) = D_q^h(z) \frac{1}{\pi \langle p_\perp^2 \rangle} e^{-p_\perp^2/\langle p_\perp^2 \rangle}$
- Then convolutions can be performed analytically to give

$$\frac{d^5\sigma^{\ell p \to \ell h X}}{dx_B\, dQ^2\, dz_h\, d^2\mathbf{P_{hT}}} \simeq \sum_q \frac{2\pi\alpha^2 e_q^2}{Q^4} f_q(x_B)\, D_q^h(z_h) \Big[1 + (1-y)^2$$

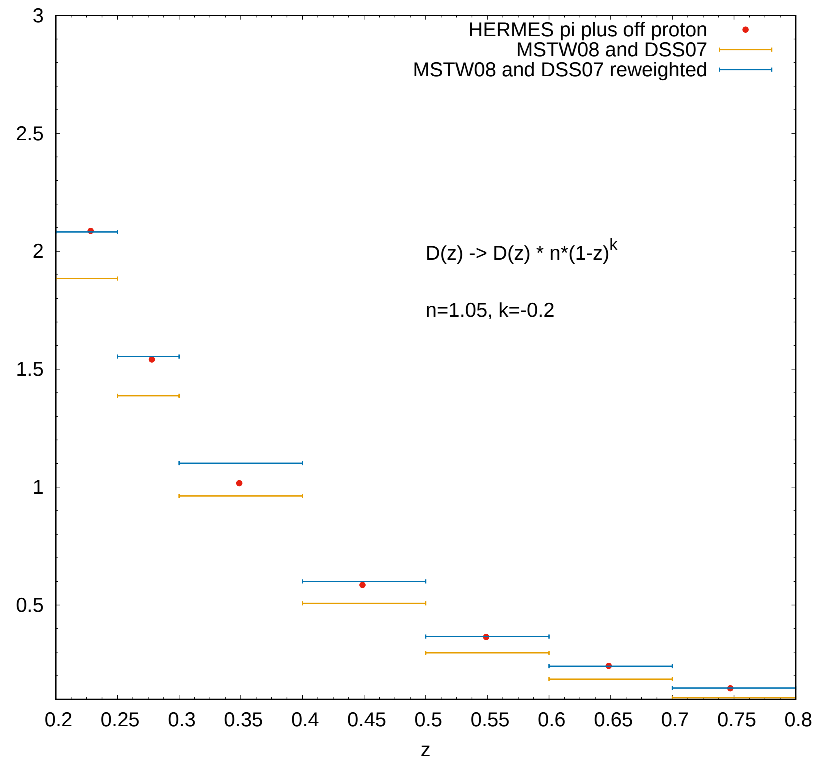
$$- 4 \frac{(2-y)\sqrt{1-y}\, \langle k_\perp^2 \rangle\, z_h\, P_{hT}^2}{\langle P_{hT}^2 \rangle\, Q} \cos\phi_h \Big] \frac{1}{\pi \langle P_{hT}^2 \rangle} e^{-P_{hT}^2/\langle P_{hT}^2 \rangle} ,$$

where

$$\langle P_{hT}^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle .$$

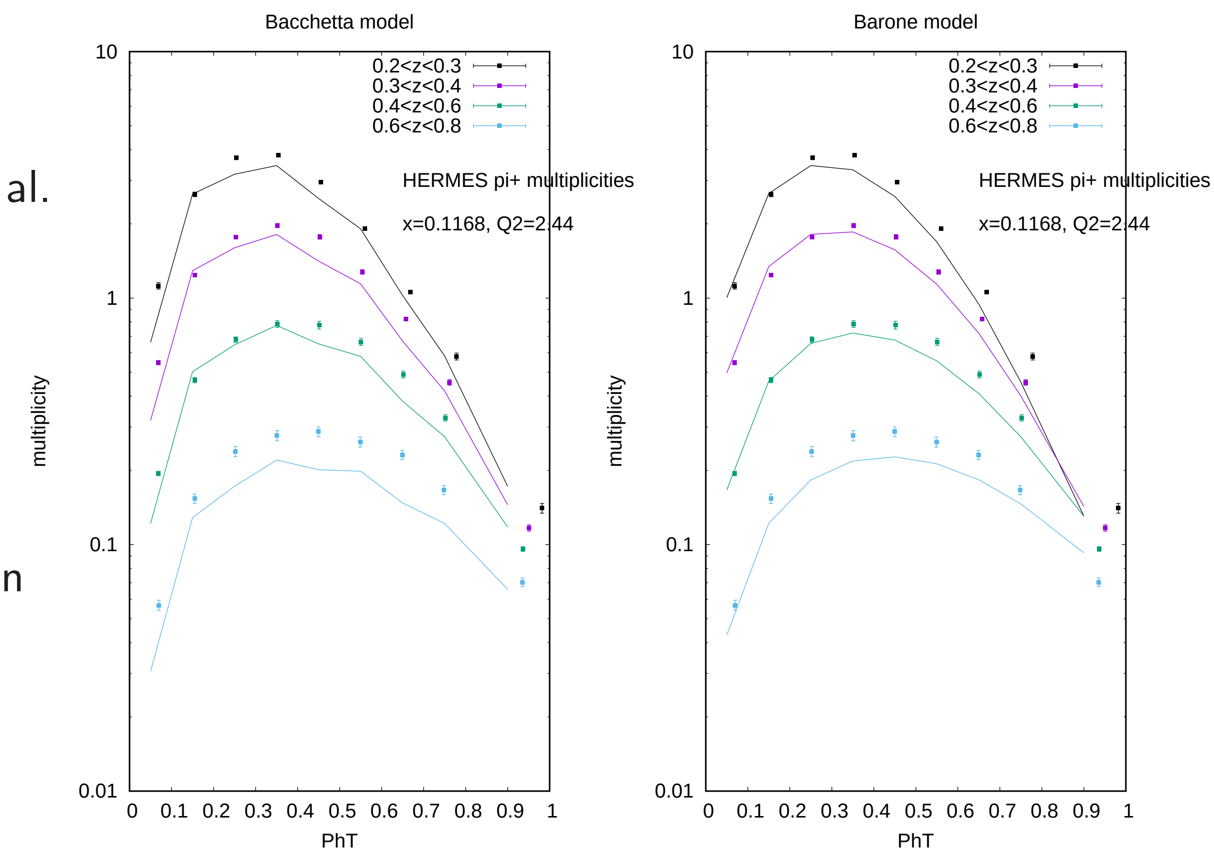
HERMES Multiplicity

- HERMES : π^+ production off proton
- $\frac{1}{\sigma_{DIS}}\frac{d\sigma}{dz}$
- Consider $\frac{1}{\sigma_{DIS}}\frac{d\sigma}{dz}$
- MSTW08 $\otimes$ DSS07
- Multiplicites allow us to check
  if z-spectra are correctly reproduced
- Description not optimal,
  reweigthing needed
- fragmentation in vacuum
  already problematic :-)



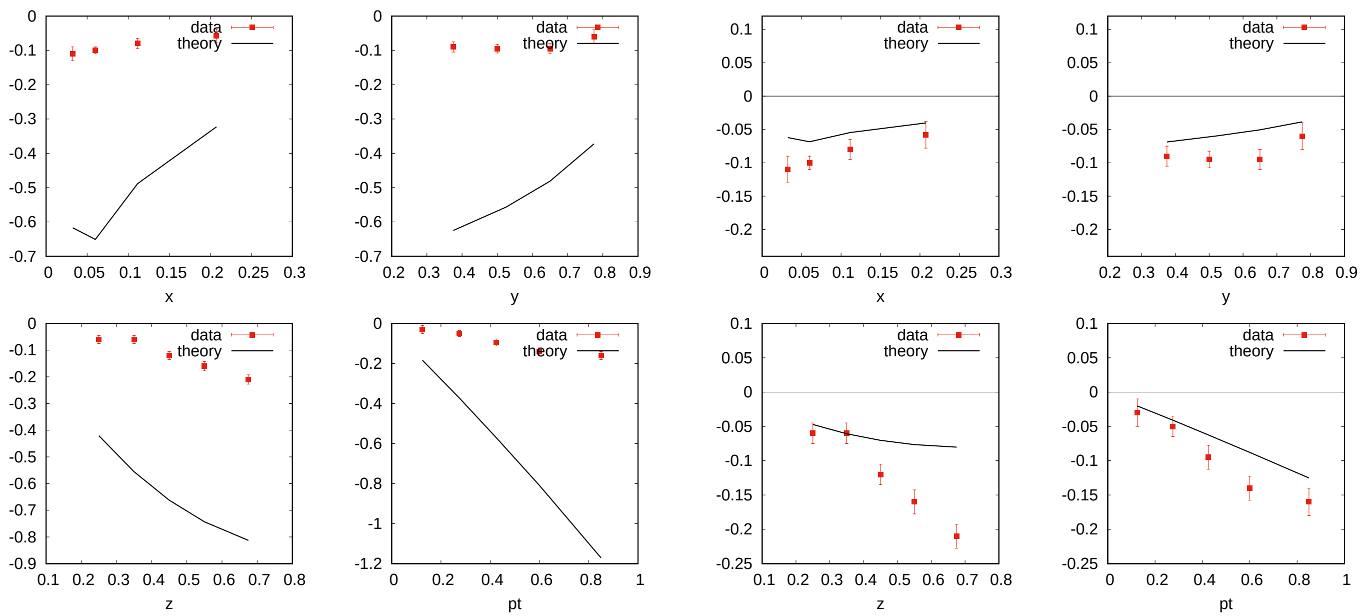
HERMES p_t-spectra

- Comparison to normalized p_t-spectra
- Left panel: model from Bacchetta et al.
- Right panel: model of Barone et al.
- $z < 0.7$ to cut exclusive production
- significant underestimation of the large z bin
- Widths are ok



HERMES $\cos(\phi)$ asymmetry

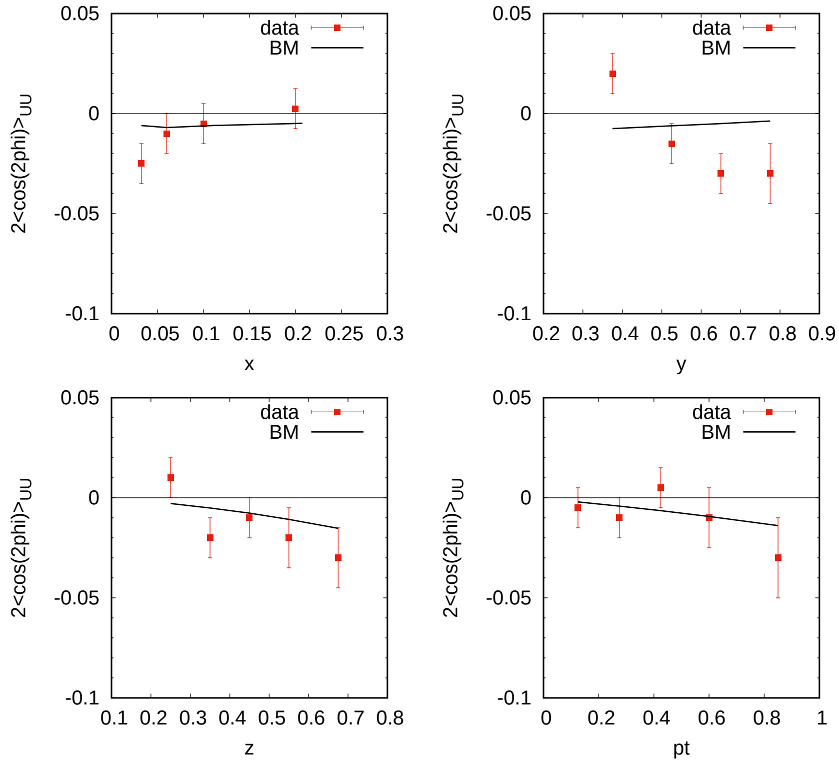
Bacchetta model | Barone model



- Reasonable description of p_t-spectra does not imply a good description of asymmetries $\longrightarrow$ large sensitivity to partonic transverse momenta.
- Here the agreement is recovered lowering $\langle k_\perp^2 \rangle$

HERMES $\cos(2\phi)$ asymmetry

- Asymmetry is leading twist
- $h_1^{\perp}(x) \otimes H_1^{\perp}(z)$
- $h_1^{\perp}(x)$ fitted:
  V. Barone et al.
  PRD 91 (2015) 7, 074019
- Collins function from
  M. Anselmino et al.,
  PRD87, 094019 (2013)



From structure functions to the asymmetry

The polarised structure function reads

$$F_{LU}^{\sin\phi_h} \approx \frac{2Mx}{Q} \sum_{q=u,d} e_q^2 \int d^2\boldsymbol{k}_T \Bigg\{ \frac{\hat{\boldsymbol{P}}_T \cdot (\boldsymbol{P}_T - z\boldsymbol{k}_T)}{zM_h} \times \Big[x\, e^q(x, \boldsymbol{k}_T^2) H_1^{\perp q} \Big(z, (\boldsymbol{P}_T - z\boldsymbol{k}_T)^2 \Big) \Big] + \frac{\hat{\boldsymbol{P}}_T \cdot \boldsymbol{k}_T}{M} \Big[x\, g^{\perp q}(x, \boldsymbol{k}_T^2) D_1^q \Big(z, (\boldsymbol{P}_T - z\boldsymbol{k}_T)^2 \Big) \Big] \Bigg\}. \quad (4)$$

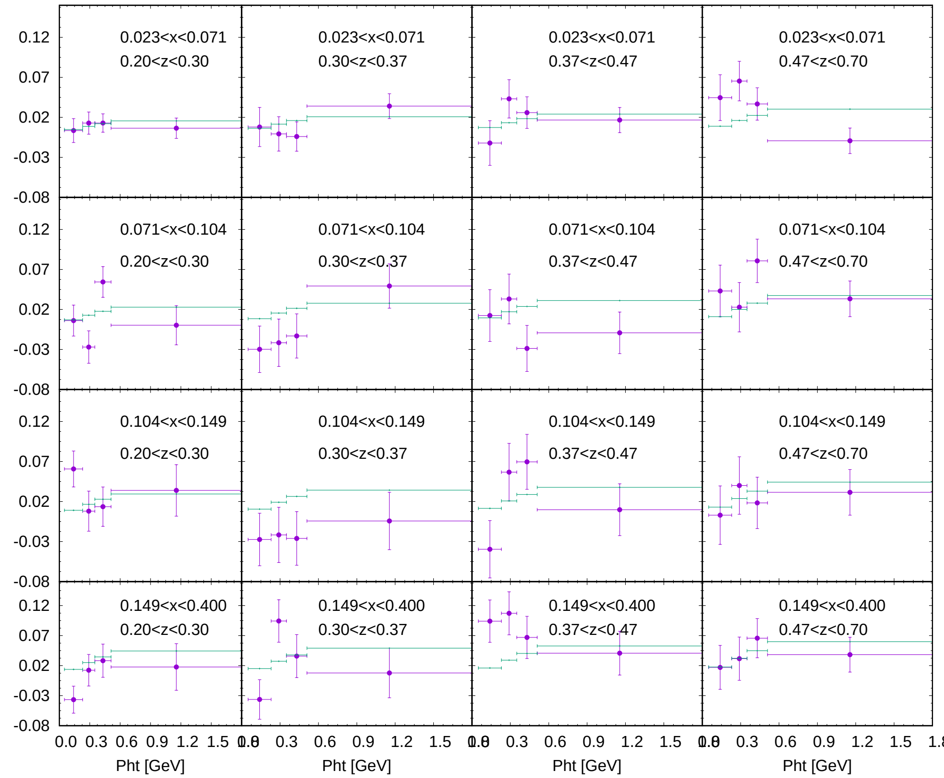
The beam SSA $A_{LU}^{\sin\phi}$ as a function of P_T therefore can be written as

$$A_{LU}^{\sin\phi_h}(P_T) = \frac{\int dx \int dy \int dz\ \mathcal{C}_{\mathcal{F}} \sqrt{2\varepsilon(1-\varepsilon)}\ F_{LU}^{\sin\phi_h}}{\int dx \int dy \int dz\ \mathcal{C}_{\mathcal{F}}\ F_{UU}} \quad (5)$$

$$\text{with}\ \ \mathcal{C}_{\mathcal{F}} = \frac{1}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \Big(1 + \frac{\gamma^2}{2x} \Big). \quad (6)$$

HERMES $A_{LU}^{\sin\phi_h}$

- Neglect $g^{\perp} \otimes D_1$ term
- Gaussian transverse factor
- Assume : $e(x) = \frac{1}{2}(1 - x) f_q(x)$
- on average, returns reasonable representation of data.
- under study:
  sensitivity to various parameters



Summary

- Phase 1
  - We have implemented all the ϕ-modulations of the SIDIS cross section
  - The task is challenging since they depend on poorly known/unknown distributions and fragmentation functions.
- Phase 2
  - We are presently running benchmark to compare with HERMES data on proton target and recently published CLAS data
  - The study of the sensitivity to cuts and paramaters is in progress
- Phase 3
  - Once completed phase 2, the goal is to extend the model in order to accomodate nuclear effects and compute predictions for next experiments